Physical Properties of White Dwarf Atmospheres

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With the advance of wide field sky surveys, such as the Sloan Digital Sky Survey and the SuperCOSMOS survey, the sample of known white dwarf stars is growing rapidly (Fig. 1). Because they represent the end stage of the life of the vast majority of stars—essentially a stellar graveyard—they can be used as "cosmochronometers" to answer various cosmological questions such as the age of the disk of the galaxy, of the surrounding globular clusters, and the first generation of halo stars. To bring this approach to its full potential requires an increased understanding in white dwarfs cooling rates.

In current white dwarfs models, the largest uncertainties currently reside in the modeling of the outer atmosphere which, in turn, requires accurate dynamical and optical properties of hydrogen, helium, and hydrogen-helium mixtures in the difficult physical regime of low temperature and high density where conventional opacity calculations fail. To address this issue, we performed Quantum Molecular Dynamics (QMD) simulations of the dynamical, electrical, and optical properties of helium for densities ranging from 0.35 to 10 g/cm^3 and temperatures less than 10,000 K. This work is further motivated by the fact that the various helium equations of state currently in use in astrophysics as well as in the SESAME tables are all adjusted to reproduce the same four experimental Hugoniot points measured below 1 g/cm^3.

QMD simulations are particularly well suited to study the physical properties of helium relevant to white dwarf atmospheres as the method provides a consistent set of dynamical electrical and optical properties from the same simulations. The physical properties are obtained within the theoretical framework of Density Functional Theory (DFT) and the electric and optical properties from the linear response theory.

In Fig. 2, we show a sample result of this study where we compare the QMD index of refraction and absorption coefficients calculated at two different temperatures and densities with the result of the latest opacity calculations developed for white dwarf atmospheres [1]. The latter model is developed within the framework of a standard opacity calculation where the classical free-free contribution is corrected for density effects. The free electron density is obtained from a chemical EOS [2, 3].

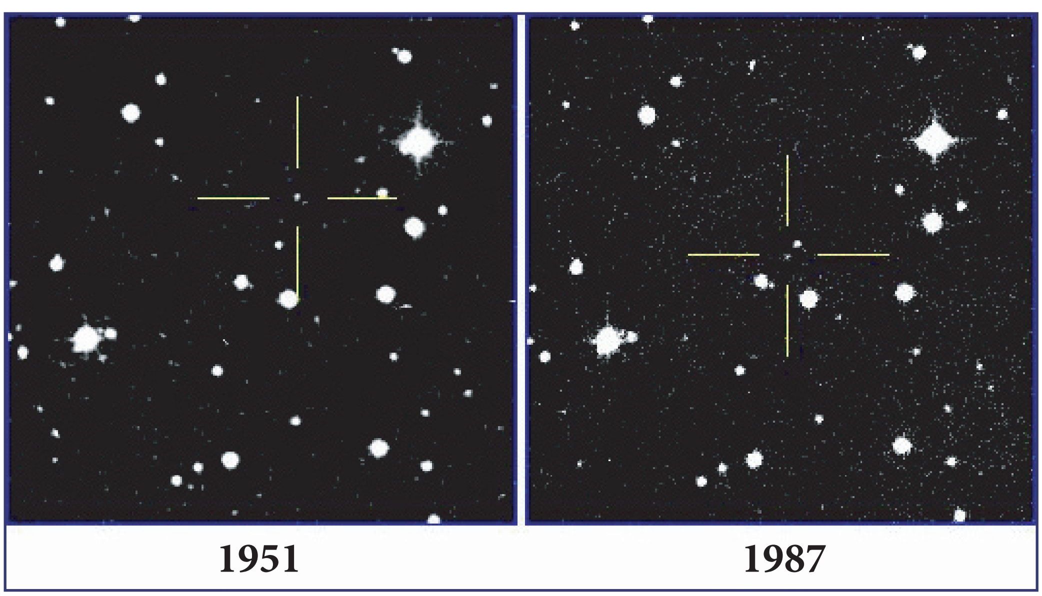

***Figure 1—** The motion of the very cool white dwarf WD0346+248 against the backdrop of distant stars between 1951 and 1987. WD0346 has a surface temperature of perhaps less than 3500 K and a surface composition of He/H ~10^3.*

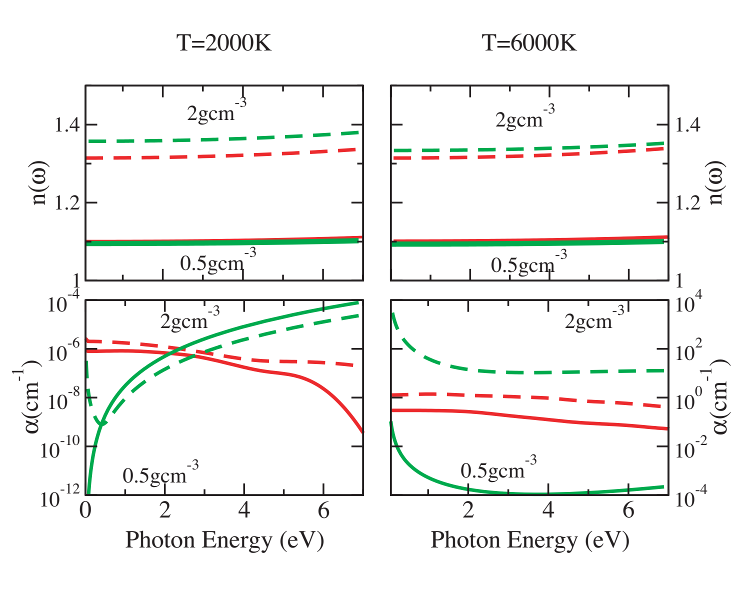

Figure 2—Comparison between the absorption coefficient and index of refraction obtained using QMD and the results of [1]: (red) QMD; (green) Iglesias et al.; (solid) 0.5g/cm^3; (dashed) 2 g/cm^3.

For the temperatures and densities shown in Fig. 2, we find a good agreement between the QMD and a virial expansion for the index of refraction. The largest difference between the two calculations appears at 2 g/cm^{3}and T = 2000 K where the virial expansion shows a stronger temperature and density dependence than the QMD calculation.

On the other hand, the absorption coefficients differ by several orders of magnitude between the two calculations. At a temperature of T = 2000 K, the opacity model indicates that Rayleigh scattering dominates the opacity down to a photon energy of 0.5 eV essentially due to the very low ionization fraction. While this effect is described classically in the opacity model, further study is required to ascertain to which extent it is accounted for in the QMD calculations. At T = 6000 K, the opacity is dominated by free-free processes and is proportional to the ionization fraction in the chemical model. At 0.5 g/cm^3, the chemical model underestimates the ionization fraction by ~3 orders of magnitude. It then rises very rapidly with density to be ~10 times larger than the simulations imply. This indicates that the pressure ionization is too abrupt in the chemical model calculation. We further note that a very good agreement between the two equations of state is found in that regime. Using the QMD calculations as reference, this comparison suggests that, in this regime of extremely low ionization fraction where the free electron density does not contribute significantly to the total pressure and energy, it may be very difficult to calculate a conventional opacity based on a free energy minimization technique as in the EOS of Bergeron et al.

Preliminary models of very cool white dwarf atmospheres of pure helium composition based on the new QMD opacities show significant departures from previous generations of models. The increased opacity results in lower atmospheric densities by factors of about 20–30. This reduces the role of density effects in the models, returning to a regime that is perhaps easier to model. The flatter frequency dependence of the opacity affects the emergent spectrum of the models. This would have immediate astrophysical consequences. First, the temperatures of the coolest helium-rich white dwarfs known would be reduced by over 10%, lengthening their cooling age. Second, none of the very cool white dwarfs would fall on the pure helium sequence, implying that they all have at least traces of hydrogen mixed in. This bears directly on ideas of the physical processes that are responsible for the evolution of the surface composition of very cool white dwarfs as they age. Finally, these new opacities are a first step toward modeling peculiar white dwarfs discovered recently that have so far defied all attempts to fit their spectral energy distributions. Those stars, such as WD0346+248, LHS 3250, and SDSS1337 are obviously very cool and apparently of mixed hydrogen/helium composition.

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[3] P. Bergeron, D. Saumon, F. Wesemael, *Astrophys. J.* **443**, 764–779 (1995).

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